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IN-SITU MAINTENANCE OF LOW-Z LIMITERS IN REACTORS

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Introduction

Although most existing tokamak reactor designs have assumed a pulsed burn, recent theoretical and experimental progress in current drive methods (rf and other) has led to a number of designs based on continuous burns, where the plasma current is maintained for periods of months.[1] While reducing the constraints on many components, steady state plasma burns increase the plasma wall loadings and reduce the scope of available maintenance procedures. We consider methods by which the surface of the first wall and limiter can be produced and maintained under these circumstances.

Sputtering Equilibria

Under normal operating conditions, the plasma should be dominated by erosion due to sputtering, arcing, and thermal desorption. Recent experiments seem to show, moreover, that arcing and thermal desorption can be minimized by careful control of the plasma operating conditions. Thus, the plasma impurity density should be controlled by sputtering yields (S_{HZ}, S_{ZZ}) under optimum conditions. These yields, based on algorithms by Smith,[2] are shown in Fig. 1 for light (B) and heavy (Ti) atoms plotted against edge electron temperature. We assume incident ion energies $E_{ion} = C<Z(T_e)>T_e$ where E_{ion} (shown in MeV) is a function of the average ion charge[3] in the sheath region $<Z(T_e)>$ and a multiplicative constant C = (0.5 - 3) which depends on the electron reemission coefficient of the surface.[4] We have indicated present uncertainty in knowledge of these yields by bars showing a factor of two in yield and also in horizontal normalization due to effects such as the sheath potential, addition of ion temperature, and electron sheath effects, etc. We define "low-Z" materials as those with $S_{ZZ} < 1.0$.

In Fig. 2, we plot the equilibrium densities[5,6] of both B and Ti impurities assuming a wall composed of 95% B and 5% Ti, using the relation:

$$n_Z/n_H = (\tau_Z/\tau_H)\,\frac{S_{HZ}}{(1-S_{ZZ})} \quad .$$

The fraction of impurities allowed for ignition is measured by the ratio:

$$r = \sum n_Z/n_{Z,crit}$$

where:

$$n_{Z,crit} = 2\,n_H/Z^2$$

is an approximation of the maximum impurity density for a given species to achieve ignition at 10 keV.[7,8] Here we have denoted the hydrogen and impurity densities and confinement times by n_H, n_Z and τ_H, τ_Z, respectively, assuming an impurity of charge Z. Once ignited, the reactor should tolerate, and may require, a higher impurity density if it is thought desirable to radiate power to the walls to limit heat conduction by the ions hitting the limiter.

Natural Erosion/Deposition Balance

Large masses of material should be moved around in a reactor by means of sputtering. Considering a geometry shown in Fig. 3 with the plasma temperature and ion flux impinging on the limiters expressed in the form:

$$T_e = T_e(a)\exp(-r/d_T)$$

and

$$F_i(r) = F(a)\exp(-r/d_i)$$

where d is the decay diffusion length, r is the minor radius, and $T_e(a)$ and $F_i(a)$ are the temperature and ion flux incident on the tip (r=a) of the limiter. We assume $d_T = d_i$, however, $d_i \neq d_Z$ in general because the decay lengths are mass dependent. These decay lengths[9] can be calculated assuming Bohm diffusion dominates in the edge region, and $d_i = d_T \sim \sqrt{D_i \tau}$, where

$$D_i(m^2/s) = 0.063\,T_i(eV)/B(T)$$

and

$$\tau = L/V_p = L/\sqrt{xT/m} \quad .$$

For tokamak reactors,[1]

$$d_i \approx 7 \text{ cm}.$$

Here, B(T) denotes the toroidal magnetic field in Teslas, V_p is the poloidal component of the thermal velocity as a function of thermal energy, kT, and

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mass m. L denotes the length over which diffusion occurs, typically the major circumference divided by the safety factor q. The net erosion rate is given by:

$$R = \int_{r=a}^{\infty} S_{HZ} F_i(r)\, dr \quad .$$

Material sputtered into the plasma will, after a time, be redeposited onto the limiter at a rate equal to:

$$D = \int_{r=a}^{\infty} (1 - S_{ZZ}) F_Z(r)\, dr$$

where $(1 - S_{ZZ})$ is equal to the sticking factor. The deposition rate, D, can be either positive, negative, or zero, depending on $(1 - S_{ZZ}(T_e))$. Steady state operation, however, requires D = R. As can be seen from Fig. 1, high-Z materials, T_i for example, require operation at low temperatures if S_{ZZ} is less than 1, i.e., $T_e \gtrsim 50$ eV. Even if the integral is positive, it should be noted that temperatures at the tip of the limiter will be much higher than any flux weighted "average" temperature. For example, defining an average edge temperature as

$$\langle T_e \rangle = \int T_e(r) F(r) dr / \int F(r) dr$$

we note that:

$$T_e(a) = 2 \langle T_e \rangle$$

assuming $d_\perp = d_\pi$. Thus, deposition at the tip of the limiter is a far more restrictive constraint than the relation D = R.

Plots of erosion and redeposition rates per absorbed flux per centimeter of minor radius, $d^2m/dEdx$ in kg/(MW · yr · cm), for heavy (Ti) and light (B) limiter materials as a function of edge electron temperature $\langle T_e \rangle$ are shown in Fig. 4. We have also indicated the erosion rates $d^2x/dtdP$ in (Å/sec · MW). In practice, these erosion rates will be reduced by a factor sin α (see Fig. 3), where sin α is likely to be less than 0.1. Because of the energy dependence of S_{HZ} and S_{ZZ}, little (if any) redeposition can occur on the leading edge of heavy limiters, however, light limiters should experience significant redeposition.

In-Situ Recoating

Ideally, in steady state devices, limiter erosion should be reduced to zero. The simplest way to eliminate erosion is to recoat in-situ, if possible during burns. This can be done by injecting pellets[10] of limiter material (at A in Fig. 3, for example). These pellets can be sized so that they completely ablate near r = a, producing a deposition profile on the limiter roughly determined by T_i and T_e profiles. The spatial distribution of this material on the limiters would be determined similarly to regular impurity fluxes, except the diffusion length, L, would be reduced due to the decreased distance between point A and the limiter edge. Thus, much of injected material could be deposited on the limiter surface after one transit around the minor circumference of the plasma, with only a fraction going into the plasma.

A "zero order" approximation of pellet deposition profiles would assume that deposition is proportional to the sticking factor times the energy flux incident on the pellet.[11] This profile:

$$G(r) = (1 - S_{ZZ}(T_e))\, T_e^{3/2}(r)\, F(r)$$

is also shown in Fig. 4.

One pellet would be able to recoat, by diffusion alone, an area:

$$A = D_\perp \tau / \sin\alpha \sin\delta$$

where δ is determined by the ratio of toroidal and poloidal fields $\delta = \mathrm{Tan}^{-1} B_p/B_\pi$. In a reactor with L = 1 m, sin α ≈ 0.05 sin δ = 0.1, and $D_\perp \tau \approx 20$ cm², the area A is reasonably large, i.e., $4 \cdot 10^3$ cm²; Since the total area of the limiter is $2 \cdot 10^5$ cm², pellets would have to be injected at roughly 50 locations around the machine, i.e., 2 - 4 pellet injection points between each pair of TF coils. Injection points would have to be moved regularly to insure complete coatings. The addition of this recoating system would be a negligible addition to the overall complexity of the reactor.

The overall erosion/deposition rates should be thus roughly equal under stable operation. It is desirable to make the overall area of the limiter region as large as possible, i.e., make α in Fig. 3 as small as possible. Assuming a net power loading of 50 MW on the limiter and an area of $2 \cdot 10^5$ cm², local erosion and deposition rates will be roughly 10 Å/s, and impurity fluxes $F_z(r)$ will be in the range $2 \cdot 10^{14}$/cm². Under these conditions, theoretical calculations have shown that radiation-enhanced solute segregation can alter solute contractions at the rate of 10 Å/s, depending on the substrate and coating material.[12] Coatings can thus be produced by decomposition of the substrate alloys.

Conclusions

In a reactor environment, the surface of a limiter or wall is primarily determined by the mechanism of erosion and deposition of surface material. It should be possible to use pellet injection to reduce net erosion to zero everywhere if low-Z materials are used for the surface. Erosion rates can, in general, be minimized by large area limiters and high plasma temperatures, which transmit power to the walls with less sputtering. Under ideal steady state conditions the wall surface is dominated by metallurgical effects in the wall.

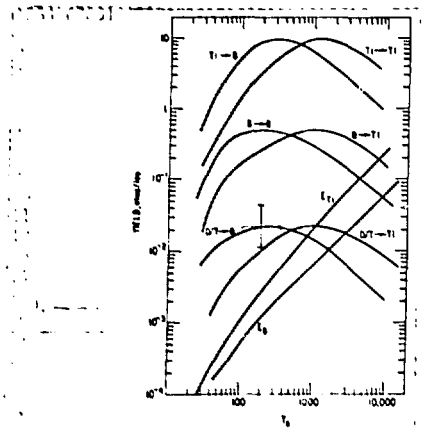

Fig. 1. Sputtering yields for different incident ions and target materials assuming a binding energy of 5 eV. Data are plotted against T_e, eV assuming $E_Z = C\langle 2(T)\rangle T_e$, with C=1. Error bars show uncertainty in yields and horizontal normalizations. E_Z is also plotted in MeV.

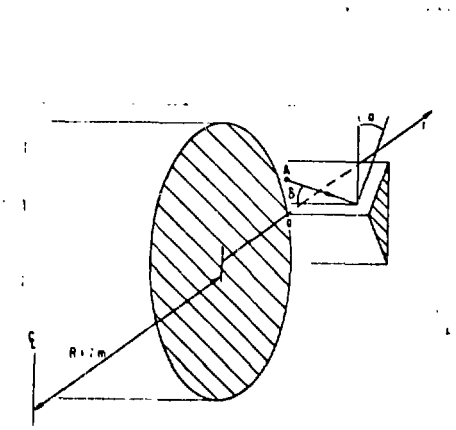

Fig. 3. Geometry of limiter in a reactor.

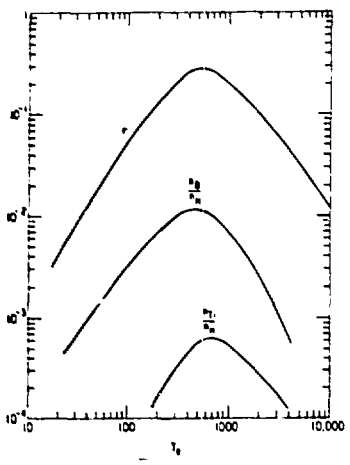

Fig. 2. Equilibrium densities for B and Ti assuming equal confinement times $\tau_H = \tau_e = \tau_{Ti}$. We have also plotted the ratio r = fraction of allowed impurities for ignition at 10 keV. These calculations assume a surface 95% B and 5% Ti.

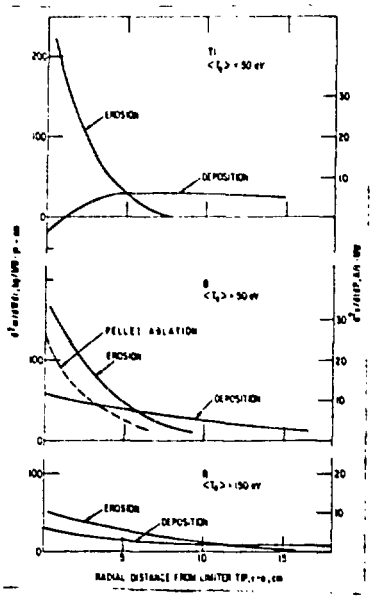

Fig. 4. Erosion rates for reactor operation plotted against distance from tip of limiter. Actual rates should be reduced by sin α (see Fig. 3). The pellet impurity production rate G(r) is also shown.

References

1. C. Baker, et al., *Starfire: A Commercial Tokamak Fusion Power Plant Study*, Argonne National Laboratory Report ANL/FPP/A-1 (1980).

2. D.L. Smith in Proc. of Workshop on Sputtering Caused by Plasma Surface Interactions, Argonne, Ill. Conf. 790775 (1979).

3. D. Post, et al., Atomic Data and Nuclear Tables 20, 397 (1978).

4. J. Brooks, J. Nucl. Mater. 94 and 95, to be published (1980).

5. D. Duchs, G. Haas, D. Pfirsch, and H. Vernickel, J. of Nucl. Mater. 53, 102 (1974).

6. J. Norem, J. Nucl. Mater. 94 and 95, to be published (1980).

7. R. Behrisch, J. of Nucl. Mater. 85 and 86, 107 (1979).

8. G. McCracken, Nucl. Fusion 19, 889 (1979).

9. R.E. Waltz and K.E. Burrell, Nucl. Fusion 17, 1001 (1979).

10. J. Norem and D. Bowers, *Thin Low-Z Coatings for Plasma Devices*, Argonne National Laboratory Report ANL/FPP/TM-108 (1978).

11. P.B. Parks, R.J. Turnbull, and C.A. Foster, Nucl. Fusion 17, 1539 (1977).

12. N. Lam, G. Leaf, and H. Wiedersich, J. of Nucl. Mater. 88, 289 (1980).